GLOBAL CARBON COUNCIL

Driving Climate Actions

Guidance for Geological CO_2 Storage

GCCM006 Guidance

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Contents

About GCC

1. The Global Carbon Council (GCC) is the Middle East and North Africa (MENA) region's first and only voluntary carbon offsetting program that aims to contribute to a vision of a sustainable and low carbon economy of the region and help to catalyze climate actions on the ground. Please refer to https://www.globalcarboncouncil.com/ for details.

2. GCC methodologies facilitate the project owners of eligible greenhouse gas (GHG) mitigation projects to calculate the emission reduction and/or removal of their projects, monitor the emission reductions/removals, develop the project submission in accordance with the methodologies, and, ultimately, access the global carbon market.

About the Guidance

3. This GCC Guidance for Geological CO_2 Storage (GGCS) version 1.0 is for the geological CO_2 storage component associated with GCC project activities that reduce GHG emissions to, or remove GHGs from, the atmosphere by capturing carbon dioxide (CO_2) that would otherwise be released to, or remain in, the atmosphere, transport it via a pipeline, rail or road tanker, and inject it into an appropriately selected and well-managed geological storage site(s) for long-term isolation from the atmosphere.

4. The GGCS is divided into five sections. Each section has been prepared cognizant of methodological requirements for crediting geological CO_2 storage project activities that were previously agreed by Parties to the UNFCCC's Kyoto Protocol in the *Modalities and procedures for carbon dioxide capture and storage in geological formations as clean development mechanism project activities* (Decision 10/CMP.7).[1] The requirements are implemented as follows:

   (a) **Section 1. Geological Storage Site Selection and Characterization**. The approach follows Steps 1 to 3 from Decision 10/CMP.7, Appendix B.1, with the addition of an optional step 0 (Site screening and selection).

   (b) **Section 2. Risk and Safety Assessment**. The approach follows a five-step process from Decision 10/CMP.7, Appendix B.2.

   (c) **Section 3. Environmental and Socio-economic Impact Assessment**. The approach implements requirements from Decision 10/CMP.7, Appendix B.6.

[1] UNFCCC, Decision 10/CMP.7. In particular, Appendix B to the Annex.

(d) **Section 4. Monitoring Requirements**. The approach implements additional geological storage site monitoring requirements from Decision 10/CMP.7, Appendix B.3. The section covers both:

(i) Initial monitoring plan design

(ii) Monitoring reports, and updates to the monitoring plan.

(e) **Section 5. Site Development and Management Plan**. The approach seeks to operationalise the findings of evaluations conducted in accordance with Sections 1-4 into an executable plan for geological storage site development. It is based on Step 4 from Decision 10/CMP.7, Appendix B.1.

5. Sections 1 to 4 are each divided into two parts:

(a) *General guidance*. Background information and the principles and concepts standing behind the guide.

(b) *Technical guidance*. A framework for approaching, implementing, and reporting the outcomes of the specific activity covered by the section.

6. Section 5 provides general guidance for approaching and reporting site development and planning.

7. In addition to the CDM standards, the guidance also implements parts of the guiding principles set out in the International Emissions Trading Association (IETA) High-Level Criteria for Crediting Carbon Geostorage activities (version 1.0).

Application of the Guidance

General applicability

8. The guidance applies to the geological storage sites that are either:

(a) Saline aquifer(s) and/or

(b) Depleted, non-producing, oil and gas reservoir(s).

9. The proposed geological storage site or storage complex must not:

(a) Be located in international waters;

(b) Present the risk of contaminating potable water resources;

(c) Traverse an international boundary (only projects that source and store CO_2 in the same host country may apply this methodology i.e., no transboundary movement of CO_2 is allowable);[2]

10. Utilization of captured CO_2 is not covered by this guidance.

11. Implementation of this guidance to a sufficiently robust standard shall:

(a) be considered to fulfil GCC methodological requirements for the geological storage site and storage complex in respect of tests, analysis, and modelling which indicate that the injected CO_2 will be completely and permanently stored such that, under the proposed conditions of use, no significant risk of seepage or risk to human health or the environment exists.

(b) not be considered as evidence that the survey, identification, and plans for CO_2 injection and storage have been permitted by a local competent authority, nor evidence of appropriate allocation of liability in the event of a net reversal of storage, including provisions for the transfer of liability for a net reversal of storage in accordance with the relevant methodology (Monitoring during the post-injection phase). This information must be compiled by project owners separate from the documentation prepared in accordance with this guidance.

12. Where this guidance, or elements thereof, are fulfilled by national laws and regulations in the country hosting the geological storage site, the requirements of relevant national laws and regulations shall prevail.

Host country reporting

13. In accordance with *Guidance on cooperative approaches referred to in Article 6, paragraph 2, of the Paris Agreement*,[3] mitigation outcomes created by geological CO_2 storage project activities must be measured using the methodologies and metrics assessed by the Intergovernmental Panel on Climate Change (IPCC).

[2] In project circumstances requiring the transboundary movement of CO_2, entities are encouraged to propose modifications to the methodology to accommodate such arrangements (e.g., where the source plant involves the capture of CO_2 in one jurisdiction, and its transport across a national border for the purposes of long-term (permanent) CO_2 storage in a different jurisdiction). Particular consideration shall be given to the appropriate permitting and liability arrangements for such circumstances.

[3] UNFCCC, Decision 2/CMA.3. Annex I, para 1(c)

14. To support host country compliance with IPCC approaches, the following documentation covered by this guidance shall be prepared and submitted by project owners alongside the Project Submission Form (PSF) for activities involving geological storage:[4]

15. Preparation of the documentation set out in the guidance therefore aligns with the following requirements set down in Section 5.10 of the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (hereafter: 2006 IPCC Guidelines), Volume 2, Chapter 5 (Carbon Dioxide Transport, Injection and Geological Storage):

    (a) Report on the methods and results of the site characterization (per Section 1)

    (b) Report on the methods and results of modelling (per Section 1)

    (c) A description of the proposed monitoring programme including appropriate background measurements (per Section 4)

    And annual reporting (per Section 4):

    (a) The mass of CO_2 injected during the reporting year.

    (b) The mass of CO_2 stored during the reporting year.

    (c) The cumulative mass of CO_2 stored at the site.

    (d) The source(s) of the CO_2 and the infrastructure involved in the whole chain of operations between the source and storage reservoir.

    (e) A report detailing the rationale, methodology, monitoring frequency, and results of the monitoring programme – to include the mass of any fugitive emissions of CO_2 and any other greenhouse gases to the atmosphere or seabed from the storage site during the reporting year.

    (f) A report on any adjustment of the modelling and forward modelling of the site that was necessary for the light of the monitoring results; The mass of any fugitive emissions of CO_2 and any other greenhouse gases to the atmosphere or seabed from the storage site during the reporting year; Descriptions of the monitoring programmes and monitoring methods used, the monitoring frequency and their results; Results of third-party verification of the monitoring programme and methods.

16. The materials prepared in accordance with this guidance therefore also fulfill host country reporting and documentation requirements relating to the implementation of the *Modalities,*

[4] Except in circumstances where the requirements set out herein for geological storage are entirely fulfilled by local regulations. In this situation, the local regulations shall prevail. Project owners are still advised to be guided by the documents set out herein and to align these with local laws and regulatory standards and requirements where applicable.

procedures, and guidelines for the transparency framework for action and support referred to in Article 13 of the Paris Agreement in respect of using methodologies, parameters and data from the 2006 IPCC Guidelines.[5]

[5] UNFCCC, Decision 18/CMA.1. Annex C.

Key Terms

17. The following description of key terms apply in this guidance:

Sr. No.	Key Term	Description
1	Bioenergy carbon capture and storage (BECCS)	The application of CCS to a bioenergy facility that emits biogenic CO_2.
2	Biogenic CO_2	CO_2 that is generated from the combustion of fuels derived from biomass or the decay (fermentation) of biomass.
3	Carbon dioxide capture and storage (CCS)	The capture of CO_2 from anthropogenic sources of emissions, and its subsequent transport to, and injection into a sub-surface geological storage site for the purpose of long-term isolation from the atmosphere.
4	Cessation of injection	The ending of CO_2 injection activities in the geological storage site, and the appropriate plugging of wells linked to the geological storage site.
5	Direct air carbon capture and storage (DACCS)	The capture of CO_2 directly from the air (atmosphere), and its subsequent transport to, and injection into a sub-surface geological storage site for the purpose of long-term isolation from the atmosphere.
6	Fossil CO_2	CO_2 that is generated from the combustion of fossil fuels (e.g., coal, oil, natural gas) or from the processing of fossil carbon in raw material feedstocks (e.g., limestone; raw natural gas)
7	Geological storage site	A paired geological formation, or a series of such formations, consisting of an injection formation of appropriate porosity and permeability into which CO_2 can be injected, coupled with an overlying caprock formation of low porosity and permeability and sufficient thickness that can prevent the upward movement of CO_2 from the injection formation.
8	History matching	The process of comparing observed results from the monitoring and measurement of a geological storage site with the results of the predictive numerical modelling of the behaviour of CO_2 injected into the geological storage site, and the use of the observed results to calibrate and update numerical models and modelling results. It can involve multiple iterations.
9	Injection formation	A carefully surveyed and selected geological formation of relatively high porosity and permeability into which CO_2 is injected for the purpose of long-term storage.

10	Liability	The legal responsibility arising from the project activity or the relevant geological storage site, including for a net reversal of storage.
11	Net reversal of storage	For a verification period during the crediting period, the accumulated verified reductions in anthropogenic emissions by sources of CO_2 and CO_2 removals by sinks that have occurred as a result of the project activity are negative (i.e., the seepage from the geological storage site of the project activity exceeds the emission reductions or removals achieved by the project activity over the duration of the verification period); For a verification period after the cessation of injection, seepage has occurred from the geological storage site of the project activity.
12	Operational phase	The period/time that begins when CO_2 injection commences and ends when CO_2 injection permanently ceases.
13	Post-injection phase	The period/time that follows the cessation of injection and ends at the point of site closure.
14	Remedial measures	Actions and measures intended to stop or control any unintended physical leakage or seepage of CO_2, to restore the integrity of a geological storage site, or to restore long-term environmental quality significantly affected by a project activity involving geological storage of CO_2.
15	Seepage	Migration CO_2 from outside of the defined boundaries of the geological storage site to shallower strata and ultimately to the atmosphere (or surface water and/or seawater in the case of CO_2 storage sites located under the seabed)
16	Significant deviation	Circumstances where monitoring of the geological storage complex indicates major variances between actual conditions relative to pre-injection predictions and observations.
17	Site closure	The point/time at which the owner or operator of a geological storage site is released from responsibilities applicable in the post-injection phase.
18	Site development and management plan	Documented description of how a geological storage site will be operated and managed.

19	Storage complex	Includes the geological storage site and surrounding geological domains that can influence overall storage integrity and security, including faults, fissures, fractures, legacy wells, overburden, and any other secondary containment formations.
20	Source plant	Process(es) occurring at a project activity site that produces a product or service and in doing so generates CO_2
21	Verification period	The period time between the submission of verified Monitoring Reports by project owners.

1. Geological Storage Site Selection and Characterization

A. GENERAL GUIDANCE FOR UNDERTAKING THE SELECTION AND CHARACTERIZATION OF GEOLOGICAL STORAGE SITES

1. Project owners shall employ appropriate geological storage site selection and characterization procedures to support assumptions regarding zero-seepage in the short-, medium- and long-term. Selection and characterisation must be supported by good management of the geological storage site and storage complex following a prescribed mode of operation that shall be prepared based on the site characteristics.

2. Where the guidance set down herein is entirely met by dedicated local regulations, the local regulations shall prevail. The guidance herein may be voluntarily adopted by project owners and/or used as a checklist alongside local dedicated regulations.

3. In the absence of dedicated local regulations, or where there is insufficient coverage of local regulations relating to all parts of geological storage characterisation and selection, the geological storage site and storage complex shall be characterized and selected in accordance with the procedures set out herein and documented following the format of the specific technical guidance contained in Part B below.

4. The "Geological Storage Site Selection & Characterisation Report" is a key component in the design of a project activity involving the geological storage of CO_2. It forms an important input to various components of the GCC approval process and cycle. Project owners should complete the report following the template provided in this guidance and submit it as an addendum to the PSF, make it available for review by the relevant host country competent authority(ies) (and its appointed bodies), and verification by an accredited entity.

5. The technical reporting template covers six key components:

   (a) The Executive Summary section

   (b) Step 0: Site screening and selection (optional)

   (c) Step 1: Data and information collection, compilation, and evaluation

   (d) Step 2: Characterization of the geological structure and surroundings domains

   (e) Step 3: Characterization of dynamic behaviour and sensitivity characterization

   (f) Step 4: Establishment of a site development and management plan (in Section 5)

6. The analysis requirements outlined in this guidance should only be implemented by specialist teams that include qualified experts as needed, such as geologists,

geophysicists, geomechanics, geochemists hydrogeologist, and petroleum and reservoir engineers.

Overview of the approach

7. Searching for and "proving" a site for geological CO_2 storage encompasses a variety of technical processes and iterative steps that can result in confidence in the integrity of containment that offers safe and sustainable injection and storage of CO_2.

8. The goal of the characterization is to assess a geological storage site and storage complex's containment, injectivity, capacity, integrity, hydrodynamics, and monitorability to ensure safe and permanent storage of CO_2. It is important to highlight that these steps are not performed purely sequentially but iteratively: during CO_2 injection, for example, the dynamic model will be updated (history matching) and used to revise the performance and the risk assessment.

9. A large and growing body of literature exists in respect of characterising sites for the sub-surface storage of CO_2. Relevant sources of information and technical guidance in undertaking **Steps 1-3** may include the following sources (and updates thereto):

   (a) ISO 27914:2017 Carbon dioxide capture, transportation, and geological storage – Geological storage.

   (b) NETL Best Practises for Site Screening, Site Selection, and Initial Characterization for Storage of CO_2 in Deep Geologic Formations - (National Energy Technology Laboratory, 2013)

   (c) Geologic Sequestration of Carbon Dioxide Underground Injection Control (UIC) Program Class VI Well Site Characterization Guidance (US Environmental Protection Agency, May 2013)

   (a) Guidance Document 2 (Characterisation of the Storage Complex, CO2 Stream Composition, Monitoring, and Corrective Measures) on Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide – (European Commission, 2011)

   (b) DNV CO2QUALSTORE Guideline for Selection and Qualification of Sites and Projects for Geological Storage of CO2; DNV Report No.: 2009-1425 (Det Norske Veritas, 2009)

10. Project owners shall refer to guidance documents, approaches, and sources of information that have been used in compiling the site characterization report.

Note the variability of the characterization process

11. Geological CO_2 storage is based largely on well-established petroleum technologies, and extensive experiences exists from CO_2-enhanced oil recovery methods undertaken in the U.S. over the past 70 years. Widespread practical implementation of site selection and monitoring for purposes of climate change mitigation remains at an early stage, however. Practices will thus likely evolve as new demonstrations or commercial CO_2 injection projects are performed.

12. In addition, the data and analysis required to assess the performance and develop different geological sites will be highly variable and will depend on the site's subsurface characteristics (depending on, for example, the reservoir homogeneity/heterogeneity, the compartmentalization, and the fault network). Thus, the storage characterization processes will always be highly site-specific.

13. The approach outlined herein includes the major components for storage site selection and characterization as broadly agreed by various stakeholders and based on a number of best practise documents. Derogations, deviations, and additions from the approach are permissible, and the rationale for such modifications should be described by project owners, drawing on experiences in developing a commercial project. Any derogations must ensure that the characterization and performance assessment indicate that under proposed conditions of use, there is no significant risk of seepage and that no significant negative environmental or health impacts are likely to occur.

14. Project owners are encouraged to highlight any independent peer review performed during the different steps of the characterization process.

B. TECHNICAL GUIDANCE FOR COMPLETING A GEOLOGICAL STORAGE SITE SELECTION & CHARACTERIZATION REPORT

Executive summary

The Project Owner shall indicate:

The name of the geological storage site and storage site	
The location (including coordinates of the boundaries) of the geological storage site and storage complex	
The version number of this report	
Date of the report	
Lead author (name, function, company)	
Lead quality reviewer (name, function, company)	

1.1 Brief description of the geological storage site

The project owner should provide a brief overview (no more than half a page) describing the appropriately selected geological storage site/complex for the project activity, highlighting:

- The name and brief description of the geology of the injection formation(s), and the overburden formation
- Injection formation characteristics (thickness; porosity; permeability; structure; fluid content; pressure; estimated total storage potential; type of CO_2 trapping mechanism(s));
- Features in the geological storage complex (wells; faults; fissures etc. in the formation).

1.2 Brief description of the characterization of dynamic behaviour

The project owner should provide a brief overview (no more than half a page) describing how the injected CO_2 can be expected to behave within the geological storage site and storage complex architecture and surrounding domains, for a range of injection scenarios with a particular focus on the risk of seepage.

1.3 Brief description of the site development and management plan

The project owner should provide a brief overview (no more than half a page) describing the site development plan including:

(a) An overview of the surface facilities
(b) The number, location and depth of injector and production wells (if relevant)
(c) The number, location and depth of monitoring wells
(d) The range of injection rates and the maximum allowable near-wellbore pressure
(e) The expected timing of cessation of injection and site closure

1.4 Interactions or conflict of use with other ongoing sub-surface or surface activities

There are a range of potential issues for competition with other sub-surface or surface uses that need to be considered. The competition can arise from surface uses, pore space being used for other purposes, and the potential seepage of CO_2 may affect the usability of other subsurface resources.

The possible interactions with other ongoing sub-surface or surface uses and potential resource conflicts should be documented by the project owners in the following table:

Type of conflict possible	Relevant for the specific storage site at the time of the permit application?		Description of the possible interaction or conflict of use	Expert-based likelihood assessment[6]
	(Yes/No)	Justification		
Oil and gas field development				
Coal bed methane production				
Coal mining				
Compressed air storage				
Groundwater				
Underground coal gasification				
Salt mining				
Geothermal				
Other CO_2 storage sites				
Surface infrastructure conflict				
Others				

Any possible interaction or conflict of use should be considered as part of the risk analysis section and a management plan should be presented (guidance in Section 2).

Step 0: Site screening and selection (optional)

The process of identifying and characterizing a geological storage complex consists of a series of assessments that progressively change scale, commencing with regional assessments, that screen and identify opportunities that are often investigated based on a broad concept of an association of reservoirs, seals, and trap types.

The final identification of a potential storage site will trigger a much more detailed assessment at a specific location. The selection of a storage site and storage complex must be based on a characterization and assessment of the potential storage site and surrounding area. Characterization of the storage complex can be mostly involved with assessments at different scales.

[6] Please use the likelihood scale developed in the Risk assessment section.

The main purpose of a characterization report is to document how the storage site(s) were selected for the project activity. However, the project owner can briefly document the steps performed to select the site(s) presented in the report as it represents an important component to reduce risk.

The project owners can document (if relevant):

(a) The screening or selection basis (including minimum acceptable criteria), including
- Geological considerations or criteria
- Technical considerations or criteria
- Legal and regulatory considerations or criteria
- Economic considerations or criteria
- Environmental, health, and safety considerations or criteria

(b) The data used during the site screening and selection process including:
- Pre-existing knowledge and data
- Newly acquired data

(c) Site or options evaluation reports including (if relevant)
- Preliminary static and dynamic modelling performed
- Preliminary performance assessment (including a preliminary assessment of capacity, injectivity, and containment)
- Preliminary risk assessment
- Other assessments performed

(d) Shortlist or selected site(s)

Step 1: Data and information collection, compilation, and evaluation.

In this section the project owner shall describe both the existing and the newly acquired data for the characterization of the geological storage site and storage complex, the determination of potential seepage pathways, and the assessment of the monitorability of the site. Quality review of the data shall be listed along with the data.

Description and evaluation of the available existing data[7]

Access to data from previous subsurface operations can support the characterization of the potential storage complex and monitoring area. If such existing data are available and are used for the characterization (including for the model construction), these data should be listed and documented using the following (or similar) template:

Data number (unique)	
Data type	
Data format	
Data acquisition date	
Location of the measurement (including depth interval if relevant)	

[7] Mainly applicable for oil and gas fields, but also applicable for aquifers.

Reprocessing (e.g., for seismic data) and reinterpretation performed (if relevant)	
Quality review performed and conclusions (including review of the applicability of the data to the current characterization)	

This section should also include regional information and data (including but not limited to hydrogeological information).

Description and evaluation of the data acquired during the characterization

Depending on the available existing data, the project owners may have acquired a range of new data solely to characterize the geological storage site and storage complex. The acquired data should be listed and documented using the following (or similar) template:

Data number (unique)	
Data type	
Data format	
Data acquisition date	
Location of the measurement (including depth interval if relevant)	
Quality review performed and conclusions	
Brief description of the processing and interpretation performed (if relevant)	

The project owners should describe (when relevant only) the following types of data acquired as part of the characterization:

(a) Well drilling report[8] and well completion report

(b) Well log and their interpretations (including well correlation cross-section)

(c) Seismic (2D and/or 3D) interpretations

(d) Results from laboratory analyses of formation fluid samples – including geochemistry, salinity, viscosity, density

(e) Laboratory analyses of core/cuttings samples:

- Lithology
- Mineralogy (matrix and cements)
- Rock properties (porosity, permeability)
- Geochemistry
- Rock mechanics
- Capillary entry pressures
- Relative permeability data
- Core flood analysis results

[8] Including key event during drilling, for example mud loss events

(f) Well tests

(g) Minifrac test description and results

(h) Other data acquired

Adequacy of the data

In this step, the project owner should document that sufficient data and information have been collected to characterize the geological storage site and storage complex to determine potential seepage pathways.

The project owners shall complete the table below (or similar) and provide a summary to explain the site-specific approach to data collection and to justify that sufficient data and information have been collected to determine potential seepage pathways. Not all information must be completed if it is not available.

	The data collected are sufficient to document/ provide: (YES/NO)	Data Number(s)	Justification
Geological information			
Descriptions of the overburden and caprock			
Descriptions of the injection formation(s), (including porosity and permeability)			
Locations of mapped faults and fractures			
Subsurface well and wellbore information			
Regional tectonics			
Pressure and temperature of the injection formation(s)			
Geophysical information			
The thickness and lateral extent of the injection formation(s)			
The thickness and lateral extent of (the) caprock formation(s) and of relevant overburden formation(s)			
Injection formation(s) heterogeneity			
Existence of faults and fracture in the geological storage site(s)			
Existence of faults and fractures in the storage complex			
Geo-mechanical information			
Geo-mechanical information within the injection formation(s)			

Geo-mechanical information within the caprock formation(s) and of relevant overburden formation(s)			
Geochemical information			
Rock and mineralogy of injection formation(s)			
Fluid properties of injection formation(s)			
Rock and mineralogy of the caprock formation(s) and of relevant overburden formation(s)			
Fluid properties of the overburden			
Hydrogeological information			
Hydrogeological information of the injection formation(s)			
Hydrogeological information of the caprock formation(s) and of relevant overburden formation(s)			
Hydrogeological information of surrounding domains.			

Step 2: Characterization of the geological storage site architecture and surrounding domains

For each model described, the project owners should indicate the version of the model presented, its date, and a brief description of the different past versions of the model (incl. key changes).

Description of the methodology applied

The project owners should describe the methodology applied to construct (a) numerical three-dimensional static earth model(s) of the geological storage site and storage complex. In particular (and when relevant), the owners should provide a brief description of the methodology (and the quality review performed) of the following steps (when relevant):

(a) Geological structure mapping/surface mapping and identification
(b) Well correlation
(c) Facies modelling (summary)
(d) Fault and fracture modelling
(e) Uncertainties analysis
(f) Upscaling process and property population
(g) Geo-mechanical properties modelling (if relevant)

Note: If an existing model is used for the site characterization (for depleted oil and gas fields) and if it is not feasible to describe the methodology applied to construct the model, the project owners should document the quality assessment performed before using the existing model(s).

Static characterization and performance assessment conclusions

The project owner should provide a summary conclusion for the following aspect of the characterization:

(a) Description of the structure of the geological containment (including overburden)
(b) Description of the injection formation(s) including lithology, age, relevant properties (physical and chemical) of the injection formation(s), reservoir heterogeneity, discontinuity, and connectivity
(c) Description of the caprock formation(s) and overburden including lithology, age, extent, and relevant properties (including secondary containment)
(d) Description of the fracture system and relevant geo-mechanical properties
(e) Estimates of the storage capacity of the injection formation(s) (including the methodology to perform the estimate);
(f) Description of the formation fluid distribution and physical and chemical properties;
(g) List of the possible CO_2 or formation fluids migration pathways
(h) Description of other relevant characteristics;

Documentation of the uncertainties

In this section, the project owner shall document the key uncertainties identified when building (the) numerical three-dimensional static earth model(s), and when relevant provide the range of value (average, low high) estimated.

The uncertainties shall be listed in the table below and shall be used for the Step 3 section.

Definition of the Uncertainty	**Source of the uncertainty**	**Average value**	**Low value**	**High value**	**Unit**

Step 3: Characterization of dynamic behaviour and sensitivity characterization

This section describes how the injected CO_2 can be expected to behave within the geological storage site architecture and surrounding domains, with a particular focus on the risk of seepage. The simulations carried out in this step shall form the basis for risk and safety assessments (see Section 2).

Description of the methodology applied for dynamic model(s) construction and simulations

The project owner should document (if relevant) for each of the models used:

(a) Version of the model, and a brief description of the different past versions of the model (incl. key changes)

(b) Scale/scope of the model

(c) Numerical simulator(s) used for the simulation, and the efficacy of coupled process modelling (see figure below on how the factors and process operating within a reservoir are "coupled") and rationale for selection of the models

(d) Methodology and results of the history matching (for oil and gas fields)

(e) Key assumptions (including boundaries conditions applied)

(f) The sensitivity/uncertainty analysis method(s) used

In addition, the project owner should provide a list of the key simulations performed. The simulations performed should consider the following:

(a) A range of possible injection rates and CO_2 stream properties to define operational constraints

(b) Short and long-term simulations (e.g., up to 1000 years)

(c) Reservoir simulations and larger scale (e.g., local or regional scale to assess effects such as pressure front migration)

(d) Sensitivities to key parameters in the static geological earth model(s) (based on the list of uncertainties prepared in the section above). The results of the sensitivity analysis performed should be referred to and used, where relevant, in the risk assessment (following the guidance in Section 2).

Dynamic characterization and performance assessment conclusions

The project owners should provide a summary of the results[9] of the dynamic simulations (including where available coupled modelling) and of the performance assessment. In particular, owners should document:

(a) CO_2 migration analysis including

- Pressure and temperature of the injection formation as a function of injection rate and cumulative injection amount over time (including pressure and temperature map in the reservoir and overburden);
- Estimates of the vertical and lateral boundaries of the subsurface CO_2 and of the formation fluid plume at given points in time and by mass of injected CO_2 through the project life (CO_2 and formation fluid saturation maps,) (including $PB_{CO2,V/L,p,t}$)
- The nature of the CO_2 flow in the reservoir, including phase behaviour;
- CO_2 trapping mechanisms and rates (including spill points and lateral and vertical seals; potential seepage rates and directions);
- Storage capacity and pressure gradients in the storage site over time.

(b) Geological storage site architecture analysis and containment assessment

- Evaluation of the trapping mechanisms present within the injection formation and any other reservoir-seal pairs in the surrounding geological storage site
- The faults and fracture system, and their respective characteristics including Fault propagation pressures (FPP), fault reactivation pressure (FRP); fault valving pressure (FVP), and fracture sealing rates (and when relevant potential related seepage rates and directions) [10]
- The condition for CO_2 entry into the caprock; (and when relevant potential seepage rates and directions) including but not limited to the maximum allowable pressure (and associated minimum temperature) at the bottom of the injection wells and in the injection formation ($P_{PC,\ SL}$).
- Changes in formation(s) fluid and mineral chemistry and subsequent reactions (for example, pH

[9] Outputs should include graphical depictions generated from model simulations at different time steps.
[10] Note that reservoir stimulation through controlled fracture should not be prohibited, provided that it does not result in a significant increase in seepage risk.

change, mineral formation); including caprock and fault dissolution properties

- Displacement of formation fluids (including rate) and the potential impact on other formations or formation fluids;
- Increased seismicity and elevation at surface level.
- Description of the containment barriers in existing and operational wells that may be reached by the CO_2 plume (based on the dynamic simulation)

C. REVIEW THE CHARACTERIZATION OF THE GEOLOGICAL STORAGE SITE

When required (e.g., in the case of a significant deviation), an update of the site characterization report shall be undertaken.

The update shall include the following steps:

(a) *Step 0*: shall not be reviewed

(b) *Review of Step 1*. Data and information collection, compilation, and evaluation: a review of the step "Adequacy of the data". Depending on the outcome of this review, new data acquisition may be required. New data acquired shall be documented as per the guidelines described in Step 1 above.

(c) *Review of Step 2*. Characterization of the geological structure and surroundings domains: Based on the new data available (from step 1 or from the ongoing monitoring) update of the Static Model(s) and review of the Static characterization and performance assessment.

(d) *Review of Step 3.* Characterization of dynamic behaviour and sensitivity characterization: Based on the revised step 1 and 2, update of the dynamic model(s) and update of the Dynamic characterization and performance assessment conclusions.

(e) This review should include a full history matching of the model(s). Project owners should follow existing best practices and industry standards to perform this history matching. The project owners should document:

(i) The methodology approach used for the history matching

(ii) A summary of the key changes in the numerical parameters (including boundary conditions)

(iii) The resulting alignment between the observed behaviour of the storage site (monitoring data) and the forecasted behaviour of the storage site

(iv) If relevant, any independent review performed.

2. Risk and Safety Assessment

A. GENERAL GUIDANCE FOR UNDERTAKING RISK AND SAFETY ASSESSMENTS

1. Project owners shall carry out a comprehensive and thorough risk and safety assessment to assess the integrity of the geological storage site and potential impacts on human health and ecosystems in proximity to the proposed geological CO_2 storage project activity.

2. The risk and safety assessment shall be undertaken in accordance with the laws and regulations of the host Party and shall be used to inform an environmental and socio-economic impact assessment.

3. Specific requirements for undertaking the assessment include:

   (a) Steps and procedures to be followed – a specific stepwise process is defined (summarised in Figure B.1);

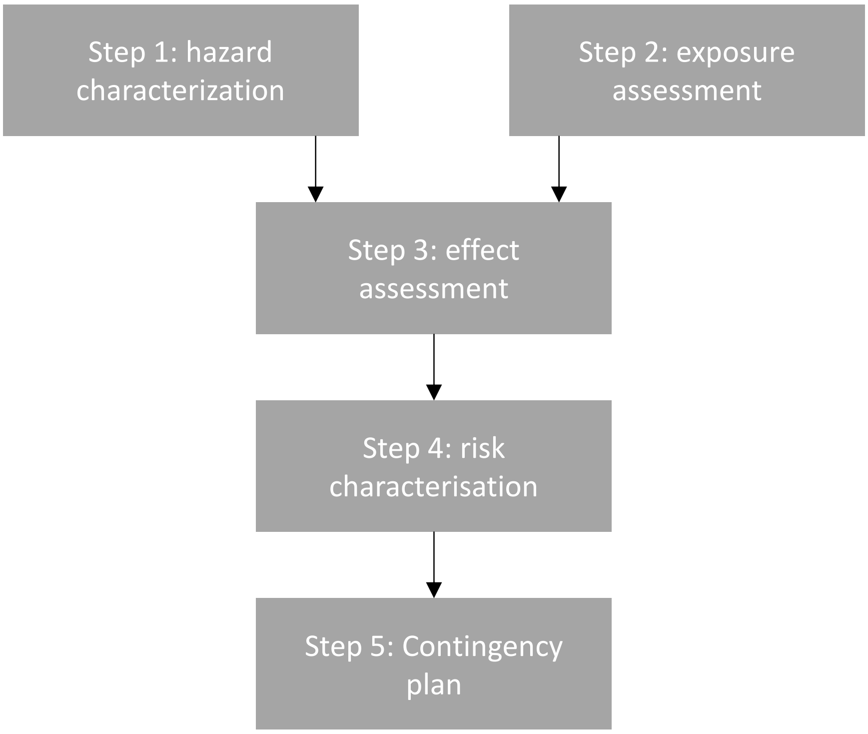
   (b) Risk scenarios to be considered (i.e., the types of events and their associated effects which could occur as a result of the project - arising from both sudden CO_2 release and longer-term containment failure; 'seepage');

   (c) Scope and content of assessment (i.e., what should be included within the assessment); and

   (d) Uses of assessment (i.e., for what purposes the risk and safety assessments should be used)

   (e) The requirements are set out in paragraphs 6-9 of Appendix B of the Annex to Decision 10/CMP.7 and should be followed by project owners in undertaking the assessment.

Figure B.1: **Step-wise Approach to Risk and Safety Assessment**



Source: based on requirements under the CCS CDM modalities and procedures (Decision 10/CMP.7)

Options to address the requirements

Step A – Review and assess national standards and regulations

4. In the first instance, project owners should review and assess host country regulations and guidance with respect to undertaking risk and safety assessments. Project owners should follow this process in accordance with national law unless good cause can be provided for any deviation from these steps.

Step B – Review and assess international best practice

5. Countries may have already established their own regulatory framework for undertaking risk and safety assessments, including for geological CO_2 storage. However, where these are deemed insufficient or lacking specific guidance in relation to undertaking geological CO_2 storage project activities, project owners should make use of existing best practice.[11] This may be required particularly in relation to those risk and safety aspects associated with

[11] e.g., ISO 27914:2017 and latest updates; DNV CO2QUALSTORE guidance

CO_2 storage where there may be limited or no host country experience and associated guidance/standards within the national regulatory framework.

6. A large and growing body of literature exists with respect of characterizing and assessing risks associated with the sub-surface storage of CO_2. Relevant sources of information and technical guidance in undertaking **Steps 1-4 (risk assessment and characterization)** include the following sources (and updates thereto):

   (a) ISO 27918:2018 CCS – Lifecycle risk management for integrated CCS projects

   (b) ISO 27914:2017 Carbon dioxide capture, transportation, and geological storage – Geological storage

   (c) Guidance Document 1 (CO_2 Storage Life Cycle Risk Management Framework) on Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide – (European Commission, 2011)

   (d) Geologic Sequestration of Carbon Dioxide Underground Injection Control (UIC) Program Class VI Well Site Characterization Guidance (US Environmental Protection Agency, May 2013)

   (e) NETL Best Practises for Site Screening, Site Selection, and Initial Characterization for Storage of CO_2 in Deep Geologic Formations - (National Energy Technology Laboratory, 2013)

   (f) DNV CO2QUALSTORE Guideline for Selection and Qualification of Sites and Projects for Geological Storage of CO_2; DNV Report No.: 2009-1425 (Det Norske Veritas, 2009)

   (g) CO_2 Features, Events and Processes (FEPs) database version 2, funded by the EU project Research into Impacts and Safety for CO_2 Storage (RISCS) - Quintessa, last updated December 2013

   (h) Risk Assessment and Management Framework for CO_2 Sequestration in Sub-Seabed Geological Structures (CS-SSGS) - adopted under the London Convention and Protocol, 2006.

7. Project owners shall make clear which guidance documents, approaches, and sources of information have been used in compiling the risk assessment for a specific project.

8. **Step 5 (contingency plans)** requires project owners to put in place all necessary response measures in case of large incidents, including seepage. These must include the availability of trained personnel, materials and equipment, and financial means to mitigate adverse impacts of the incident and teams prepared to act as swiftly as possible. As per Steps 1-4, project owners should refer to existing international best practice and guidance where appropriate. These include provisions contained within for example the regulations

developed in both Europe and the U.S. for CO_2 storage, namely the EU CCS Directive and the U.S. EPA UIC Class VI well rule.

9. These regulations contain requirements for storage site operators to undertake the following:

   (a) *EU CCS Directive* - Submission of Corrective Measures Plan outlining measures related to the protection of human health in cases of leakages and significant irregularities which imply the risk of leakage

   (b) *US EPA UIC Class VI* - Emergency and Remedial Response Plan that describes the measures that would be taken in the event of adverse conditions at a geological sequestration project, covering, for example: as a loss of a well's mechanical integrity, or if movement of injection or formation fluids caused an endangerment to an Underground Source of Drinking Water (USDW)

10. The regulating authorities under both rules have issued guidance on the approaches that may be taken to meet these requirements, which can be referred to as best practise sources by project owners, namely:

   (a) Guidance Document 2 (Characterisation of the Storage Complex, CO_2 Stream Composition, Monitoring and Corrective Measures) on Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide (European Commission, 2011)

   (b) Geologic Sequestration of Carbon Dioxide Underground Injection Control (UIC) Program Class VI Well Project Plan Development Guidance, (US Environmental Protection Agency August 2012)

11. In all cases, project owners should fully reference and explain the use of best practise and technical guidance used in undertaking Steps 1-5 of the assessment.

12. The analysis requirements outlined in this guidance should only be implemented by specialist teams that include qualified experts as needed, such as geologists, geophysicists, geomechanics, geochemists hydrogeologist, and petroleum and reservoir engineers.

B. TECHNICAL GUIDANCE FOR COMPLETING A RISK AND SAFETY ASSESSMENT REPORT

Information to be included alongside the PSF

B.1 Introduction

The name of the geological storage site[12] and storage complex	
The location (including coordinates of the boundaries) of the geological storage site[13] and Storage site	
The version number of this report	
Date of the report	
Lead author (name, function, company)	
Lead quality reviewer (name, function, company)	

B.2 Documentation of the Methodology

To perform a comprehensive hazard identification and risk assessment, a structured process is required to ensure that the collection of potential risk scenarios is as complete as possible based on the available data.

The risk assessment report should thus contain a detailed description of the methodology used for steps 1 to 5 outlined above. The methodology should use existing best practice guidelines and documents. In particular, the documentation should be sufficiently comprehensive to allow the project developer or an external verifier to revisit the initial risk register and understand the reasoning for the analysis of each individual risk.

If the risk analysis involves an expert workshop, this workshop should be described with details such as when and where it was carried out, the names and functions of the experts attending the workshop, data sources used in the workshop, and documents produced from the workshop.

Cross-references to the site characterization report, and to the modelling results, should be explicitly provided. Indeed, models may be used to predict the probability (and rates) of potential seepage through wells or other features. Moreover, by performing simulations on multiple geostatistical realizations of the storage site, it should be possible to estimate the likelihood for plume evolution scenarios that cause risks to be materialized or signal the need to implement additional preventive measures.

Finally, the project risk assessment matrix (definitions that are used to rank consequences and likelihood of risk scenarios) should be described, including the methodology used to develop this matrix and how the definitions used relate to the specific host countries circumstances and regulations, where applicable. The project owner should also describe the methodology/approach that has been used to define the level of acceptable risk.

B.3 Risk Register

Project owners should consider summarising the results of risk and safety assessments in an initial risk register, which sets out, *inter alia*:

(a) Risk number and name

[12] As defined in the M&P
[13] As defined in the M&P

(b) Details of specific features that could present a risk

(c) The types of processes that could occur to activate the identified feature (causes)

(d) The consequences of feature activation (secondary effects such as displaced formation fluid should also be documented)

(e) The description of the existing barriers or safeguards in place to prevent either the activation of the feature or the consequence. This includes secondary containment[14].

(f) The type of approach (Qualitative, Quantitative, or semi-quantitative) used for the risk ranking/assessment. Although certain risks may be quantifiable, it is recognized that many risk scenarios will not be readily quantifiable due to a lack of statistical data or quantitative risk indicators

(g) Detailed basis and rationale for grading and ranking of the risk scenarios

(h) Risk assessment (likelihood and consequence /severity assessment). As per best practices, risks should be graded and ranked conservatively in the presence of uncertainty.

(i) Documentation of the key sources of uncertainties: Lack of knowledge on the likelihood and consequence of identified hazards is not a risk “per se”, but has an impact on how risk is evaluated, and should therefore be documented. Uncertainties inherent in the data should be identified and described in such a way that uncertainty-reducing measures can be identified and implemented.

(j) Risk owner

B.4 Risk Management

The objective of this step is to identify mitigating actions and safeguards, including monitoring, preventive and corrective measures, and other types of action, that can be used to reduce the risks and/or uncertainty for the identified risks.

Contingency measures would be identified for implementation or planning at different stages of the life cycle. Safeguards are expected to avoid the risks from developing into irregularities or seepage or to mitigate their effects.

Safeguards may be preventive or corrective.

(a) **Preventive safeguards** can be implemented prior to the event to reduce the probability of an incident occurring or reduce the impact associated with an incident if it occurs.

(b) **Corrective measures** are safeguards that are implemented to correct significant irregularities or seepage to prevent or stop the release of CO_2 from the storage complex.

For each safeguard, an assessment of the risk reduction effect of the alternative safeguards for the associated risk should be evaluated which may be either qualitative or quantitative. If the effect of the safeguard is uncertain, the uncertainty should be accounted for conservatively.

Identified safeguards should be prioritized according to their cost-effectiveness. The project owner should then describe the risk management measures and how the risk management measures will impact the risk assessment/ranking.

[14] Secondary containment: an assessment of any additional subsurface containment systems present within the geological storage site. This introduces an enhanced safe-storage concept with increased operating safety margins that is analogous to an engineered storage system such as an oil storage tank farm. In subsurface terms, this may mean a primary geological storage site with primary caprock formation with additional containment potential provided by subsequent (non-sensitive) containment systems or through extensively connected pore space that allows attenuation (in open-ended formations). These additional containment systems (secondary, tertiary, etc.) are safety features designed in such a way that migration across the boundaries of the injection formation does not lead to migration of injected CO_2 to areas with known features that could have connectivity to the atmosphere/hydrosphere (i.e., seepage pathways).

Risk management may include:

1. *Eliminate*: eliminate the hazard (e.g., removing one of the injections well in the project construction plan)
2. *Substitute*: use processes or methods with lower risk impact (e.g., change the location of the injection well)
3. *Isolation/separation*: segregate hazard or target (e.g., ensuring that sufficient spatial and temporal separation exists between the CO_2 plume and identified and characterised seepage risk features/ processes and sensitive surrounding domains, e.g., old wells.)
4. *Engineer safeguard, prevention*: design to prevent the unwanted event (e.g., planned injection and production wells count and design; tubular connections; materials selection; cement integrity; well trajectory planning and zonal isolation, in particular best-in-class cementing practices, re-entering and re-plugging existing wells)
5. *Monitor (detection and surveillance)*: to detect early signs of irregularities (e.g., unintended/unanticipated CO_2 plume migration; feature activation), determine their significance. The procedures for design and updates of monitoring plans are described in Section 4.
6. *Engineer safeguard, recovery*: design to mitigate harmful consequences (reproduce injected CO_2)
7. *Organisational control*: training competency, communication
8. *Procedural controls*: operating procedures work instructions, permits, maintenance regime, emergency response procedures. (The maximum tolerable injection pressures: the project owner should document the methodology used to determine pressure safety factor; P_{SF})
9. Personal protective equipment

The risk management plan should include contingency plan for large incidents, including seepage. The contingency plan should include all the necessary plans to be put in place in case of large incidents, including availability of trained personnel, materials and equipment and financial means to mitigate adverse impacts of the incident and teams prepared to act as swiftly as possible.

The risk management plan may include a risk communication plan. The risk communication plan should include description of the interactive exchange of information about risks among risk assessors, managers, media, interested groups and the public.

B.5 Update of the risk assessment

Project owners should document how risks and uncertainties are effectively managed and reduced over time. The risk assessment should thus be reviewed on a regular basis during the project lifetime but also in the event of a significant deviation.

The risk assessment update should include for each of the change at least the following:

(a) The date of the change

(b) The details of the changes in the risk register (see details on the content of the risk register in section D1)

(c) The rational for the changes performed.

(d) The person who performed the changes

The process should be properly documented to allow a verifier to review the full history of the risk assessment. All revisions to the risk register should thus be retained for quality control of the risk management process itself and of the evolution of the risk as per existing best practises.

3. Environmental and Socio-Economic Impact Assessment

A. GENERAL GUIDANCE FOR UNDERTAKING ENVIRONMENTAL AND SOCIO-ECONOMIC ASSESSMENTS

1. Project owners must undertake an *environmental and socio-economic impact assessment* for the proposed project activity. This adopts the requirements set out in paragraphs 26 to 29 of Appendix B to the Annex of Decision 10/CMP.7, namely that owners should:

   (a) analyze thoroughly and exhaustively air emissions (nitrogen oxides, sulfur oxides, dust, mercury, polycyclic aromatic hydrocarbons, etc.), solid waste generation, and water use associated with current CCS/DACCS/BECCS technologies;

   (b) apply the best available techniques to facilitate a high level of protection for the environment as a whole and communities;

   (c) include a comprehensive analysis of the environmental and socio-economic impacts; and

   (d) invite comments from local stakeholders, and demonstrate how due account has been taken of any comments received

Options to address the requirements

Step A – Review and assess national standards and regulations

2. In the first instance, project owners should review and assess host country regulations and guidance with respect to undertaking environmental and socio-economic impact assessments. These should be followed, whilst demonstrating that the requirements under Decision 10/CMP.7 as set out above are met.

Step B – Review and assess international best practice

3. Most countries have established national environmental impact assessment (EIA) or environmental and social impact assessment (ESIA) requirements by law for major infrastructure projects. These requirements may be conferred onto CO_2 geological storage activities through the implementation of national laws and policies.

4. However, arrangements established by individual countries can differ in their scope, content, and detail. For example, assessments required under the host country's national law may or may not include requirements and procedures to address non-environmental aspects (e.g., social, and economic impacts).

5. In such cases, project owners should ensure that assessments are undertaken according to international best practice and guidelines. Examples may include:

   (a) arrangements and standards required by multilateral financial institutions as part of their lending requirements such as the IFC and World Bank Group Environmental, Health, and Safety Guidelines;

   (b) EIA principles issued by the International Association for Impact Assessment (IAIA), the UK Institute of Environmental Management and Assessment (IEMA) and other similar organizations

   (c) standards established by the International Organization for Standardization (ISO 14000 series; Environmental Management Systems)

6. Host countries may have little or no experience in undertaking assessments for CCS/DACCS/BECCS projects. Most activities associated with a CCS/BECCS/DACCS project are, however, well-established industrial practices and fall within the environmental and health and safety frameworks of the relevant jurisdiction in terms of required emissions limits, standards, and practices.

7. Similarly, for new build projects, such activities are subject to the same regimes of permitting and planning consent as other industrial projects, including legal requirements for undertaking impact assessments. The major surface components of a CCS/DACCS/BECCS project (CO_2 source, capture installation, transport installation, wells, and any surface facilities at injection sites) are in general covered by existing EIA laws or through international and corporate standards. Similarly, surveying activities such as seismic acquisition are also typically covered by appropriate arrangements (IEA 2010).[15]

8. Geological CO_2 storage sites may, however, present a challenge within existing host country arrangements because of the novel nature of the activity. Environmental, health, and safety considerations must include an assessment of whether the storage site could pose a potential threat to any sensitive ecosystems or human populations or have access challenges for development and maintenance. Project owners should therefore review and refer to international best practice and technical guidance in respect of assessing impacts associated with CO_2 storage. Best practice procedures for undertaking EIA for CO_2 storage sites are still being developed. The IEA Greenhouse Gas R&D Programme has produced a report on EIA requirements for CO_2 capture and storage[16] and a rich body of technical literature exists with respect to best practice for identifying, assessing, and monitoring CO_2 storage sites, which include guidance relating to identifying, assessing, and managing impacts, as outlined in Section 2. Furthermore, EIA and ESIA have been published for

[15] IEA 2010. Model Regulatory Framework for CCS
[16] Environmental Assessment for CO_2 capture and storage. Technical Study; Report Number 2007/1. March 2007

several large-scale CCS/DACCS/BECCS projects worldwide, which provide an additional source of best practice guidance, depending upon the specific details of the project activity.

9. Project owners shall make clear which guidance documents, approaches, and sources of information have been used in compiling the impact assessment for a specific project.

10. Project owners should ensure that the impact assessment is undertaken cognisant of the Base Level Survey (see Section 4).

B. TECHNICAL GUIDANCE FOR COMPLETING AN ENVIRONMENTAL AND SOCIO-ECONOMIC ASSESSMENT REPORT

Information to be included alongside the PSF

As per the General Information in Part A, project owners should in the first instance refer to existing host country guidance and regulation in preparing the assessment, making use of best practice guidance where appropriate. A report of the assessment should be included alongside the PSF, and as a minimum should include the following components:

1. Description of the applicable or parallel policy, legal, and regulatory frameworks that could pertain to the geological CO_2 storage activity (including the applicable performance standards, protocols, and guidelines used in the assessment)
2. Project description (this should describe the planned project in detail, including the period of construction, operation, and decommissioning, and may draw upon relevant information presented in the PSF)
3. Description of the local environmental and socio-economic conditions (e.g., a baseline description of the physical, biological, and socio-economic environment)
4. Anticipated environmental impacts (a comprehensive assessment of impacts covering soil, land use, air quality, water, noise, flora and fauna, sites of cultural significance, human health and safety, socio-economic impacts, visual aspects, and traffic and transportation)
5. Summary of mitigation measures (identification of the significance of impacts, and a description of the mitigation and remedial measures to be put in place)
6. Information on public participation and consultation

Any supporting technical information (which may be provided in the form of web links to existing documentation e.g., results of air dispersion modelling; baseline environmental surveys; environmental audits, etc)

C.1 Scope of the Assessment

Adequate scoping of the full range of potential impacts arising from the project activity is key to ensuring that project participants undertake a *comprehensive* analysis. In line with best practise, such assessments should consider the full scope of potential impacts arising across all components of the CO_2 capture, transport, and storage chain, and potential incidental effects (e.g., potential impacts of biomass supply in BECCS projects; materials and chemicals consumption for CO_2 capture).

Where the operation of CO_2 capture results in a change in the performance of a source plant, the cumulative impacts associated with that activity and the CO_2 capture must be considered within the scope of the assessment. For example, this could occur where the operation of a capture facility results in increased emissions from the source plant (from which the CO_2 stream is captured).

All stages of a CO_2 capture, transport, and storage chain may give rise to potential environmental impacts, with associated risks to the environment and human health. Most of these are well understood and are similar to those associated with other industrial facilities. These include e.g.,

- *Capture*: atmospheric emissions; wastewater discharges; solid waste generation; additional energy and other resource use (e.g., use of chemicals incl. amines)
- *Transport*: atmospheric emissions; land-use impacts; additional energy use
- *Storage*: atmospheric emissions; wastewater discharges; additional energy

CO_2 capture, transport, and storage project activities may however give rise to specific additional or novel issues which must be reflected in the assessment. These include e.g.,

(a) **CO_2 storage:** consideration of the potential sub-surface and surface impacts arising from the movement of the CO_2 stored within the geological storage site, including seepage to the atmosphere. A release of CO_2 to the surface can potentially result in asphyxiation and ecosystem impacts as well as impacting ground- and surface water quality. The assessment of these aspects is a key consideration during the identification and characterization of the geological storage site(s) (Section 1).

(b) **Impacts arising from the presence of certain substances and impurities in the captured CO_2:** depending upon the source of the CO_2 and the capture process deployed, the CO_2 stream leaving the capture facility may contain various substances and/or impurities. These may adversely affect the integrity of the storage site or the relevant transport infrastructure (i.e., corrosion and impact on fluid characteristics) and if toxic, potentially pose additional risks to the environment and human health and safety.[17]

(c) **Health and safety risks associated with CO_2:** occupational and local environmental, health and safety risks may be posed by the presence of large volumes of pressurized CO_2 at capture facilities, injection facilities, and storage sites. Several standards have been established internationally for CO_2 exposure and handling, and project owners should demonstrate that these or equivalent domestic host country standards will not be exceeded through the operation of the project. Relevant standards include for example exposure limits outlined under the US Occupational Safety and Health Administration (OSHA) General Industry Permissible Exposure Limit (PEL) and US Department of Energy (DOE) Protective Action Criteria (PAC) levels.

Environmental and socio-economic impact assessments shall also include a detailed description of the planned mitigation and remedial measures to address any impacts identified.

In addition, a comprehensive environmental monitoring plan must be prepared by the project owner, detailing which environmental parameters will be monitored and the techniques/methodologies to be employed.

As such, the assessment should also draw upon and be informed by the project monitoring plan (see Section 4). These different project components[18] are closely linked and project owners should demonstrate how a change in one component might require a material change in another. For example, re-characterizing the geological storage site may require revision of the project boundary and monitoring plan, and trigger changes to the risk and safety assessment and the environmental and socio-economic impact assessments.

Similarly, geological storage sites shall only be used to store CO_2 as GCC project activities if, under the *proposed* **conditions of use**, it can be demonstrated that there is no significant risk of seepage.

C.2 Public Participation and Consultation

Project owners should provide information on how the assessment process included meaningful public participation and consultation (i.e., comments were invited from local stakeholders, and due account was taken of any such comments received).

In line with best practice, the process should provide for public notification, disclosure of information on the project and its anticipated impacts, access to relevant documentation, and comment by affected and interested parties on scoping and assessment reports.

In addition, the procedures for public consultation should allow for all interested and affected parties to express their views beginning early in the process and continuing throughout.

Many jurisdictions will already have existing regulatory provisions dealing with public consultation procedures, usually as part of planning law frameworks and linked to the environmental impact assessment (EIA) laws and procedures.

In general, international case studies and the EIAs of CO_2 capture, transport and storage projects undertaken to date show that effective engagement includes ensuring that the local community and other stakeholders have:

(a) Access to reliable information

[17] The EC has produced a guidance note describing the potential concerns associated with the CO_2 stream composition, which provides a useful scope of issues for consideration and assessment within the EIA process: "Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide: Guidance Note 2 – Characterization of the Storage Complex, CO_2 Stream Composition, Monitoring, and Corrective Measures."

[18] namely: identification and characterization of the geological storage site; risk and safety assessment; monitoring plan; and environmental and socio-economic impact assessment

(b) An opportunity to raise concerns

(c) An opportunity to receive a response to concerns (written or verbal) and to have concerns addressed by alterations in the project design

(d) An agreement on the decision-making process with an opportunity to provide input before decisions are made

(e) Community involvement in decision-making, where warranted

(f) A priority for all parties to reach mutually agreeable outcomes on key issues

(g) Proper development of mechanisms for benefits-sharing

Project owners should refer to existing best practise guidance in the development of the public engagement process. The World Resources Institute (WRI) *Guidelines for Community Engagement in CCS Projects* provide one such source of best practice actions that can be used as a useful guide to ensure effective public engagement with respect to CCS/DACCS/BECCS projects. Others include the *Lessons from Project Level Community Engagement* produced by the Western Australian Department of Mines and Petroleum.

Table C.1: **Roles of various stakeholders in the community engagement process for a CCS project**

Regulators	Local Decision-makers	Project Developers
Understand the Local Community Context		
Learn community concerns. Determine, meet, and possibly improve public participation requirements.	Understand community interests, identify leaders, and establish a dialogue early	Assess community dynamics and your historical presence and weigh participatory engagement.
Exchange Information about the Project		
Educate, respond to, and provide information to the public	Contact developers early. Ask questions. Identify, seek, and publicize pertinent information about the project	Engage early and develop a relationship with the community. Answer questions. Seek input, and provide information openly and transparently
Identify the Appropriate Level of Engagement		
Establish a multi-stakeholder engagement process	Determine engagement level and establish a transparent process	Foster two-way engagement: consult and negotiate with communities. Address concerns. Convey a feasible level of engagement
Discuss Risks and Benefits of the Project		
Require communication and contingency measures and regular updates during the life cycle. Evaluate environmental and other impacts	Ask questions. Identify and communicate concerns and clarify the follow-up process. Insist on full disclosure	Answer questions. Discuss with community risks, benefits, uncertainties, and mitigation and contingency plans. Consider benefit sharing
Continue Engagement Throughout the Project Life Cycle		

Regulators	Local Decision-makers	Project Developers
Require public participation at key stages and increase engagement in the process	Establish institutional memory, possibly a task force. Consider participating in monitoring and reporting Regularly update the community	Engage the community at each step of the project schedule Consider informal, long-term relationship to ease stewardship transition

Source: WRI Guidelines for Engaging Local Communities in CCS Projects, 2010

4. Monitoring Requirements

A. GENERAL GUIDANCE FOR GEOLOGICAL STORAGE SITE MONITORING DESIGN

1. Appropriate subsurface monitoring is the most important method for assessing CO_2 storage performance in a geological storage site. Drawing from Appendix B of the Annex to Decision 10/CMP.7 (para. 10), the objectives of monitoring of geological CO_2 storage sites include:
   - (a) To assure the environmental integrity and safety of the geological storage site;
   - (b) To confirm that the injected CO_2 is contained within the geological storage site and the project boundary;
   - (c) To ensure that injected CO_2 is behaving as predicted to minimize the risk of any seepage or other adverse impacts;
   - (d) To ensure that good site management is taking place, taking account of the proposed conditions of use set out in the site development and management plan,
   - (e) To detect and estimate the flux rate and total mass of CO_2, in the event of any seepage;
   - (f) To determine whether timely and appropriate remedial measures have been carried out in the event of seepage;
   - (g) To determine the reductions in anthropogenic emissions by sources of greenhouse gases that have occurred as a result of the registered CO_2 capture, transport, and storage project activity.

2. In addition, geological CO_2 storage site monitoring should:
   - (a) Reflect the principles and criteria of international good practice for the monitoring of geological storage sites and consider the range of technologies described in the relevant sections of the IPCC 2006 IPCC Guidelines and other good practice guidance. This would ensure the monitoring is aligned with:
     - (i) *Guidance on cooperative approaches referred to in Article 6, paragraph 2, of the Paris Agreement* (Decision 2/CMA.3) and the requirement therein to use methodologies and metrics assessed by the IPCC; and
     - (ii) *Modalities, procedures, and guidelines for the transparency framework for action and support referred to in Article 13 of the Paris Agreement* (Decision 18/CMA.1) in respect of using methodologies, data and parameters from the 2006 IPCC Guidelines.
   - (b) Transparently specify which parameters and information will be monitored and collected, and the location and frequency of application of different monitoring techniques during the operational phase and post-injection phase;
   - (c) Provide for specific techniques and methods that can:
     - (i) Detect and estimate the quantity of the CO_2 stored in the geological storage site;

(ii) Detect potential seepage via pathways in the caprock formation(s) and in the overburden and surrounding domains in the geological storage complex;

(iii) Estimate the flux rate and total mass of CO_2 emitted from any seepage;

(d) Include provisions for history matching, by using the monitoring results to calibrate and update the numerical models that were used to characterize the geological storage site;

(e) Provide for measurement of the temperature and pressure at the top and bottom of the injection well(s) and observation well(s), at an appropriate frequency;

(f) Provide for the monitoring and measurement of various geological, geochemical, and geomechanical parameters, such as fluid pressures, displaced fluid characteristics, fluxes, and microseismicity, at an appropriate frequency;

(g) Provide for the monitoring and measurement of relevant parameters in the overburden and surrounding domains of the geological storage complex, such as the monitoring of groundwater properties, soil gas measurements, and measurements of the surface concentrations of CO_2 in the air, which shall be calibrated to detect signs of seepage, at an appropriate frequency;

(h) Provide for the detection of corrosion or degradation of the transport and injection facilities;

(i) Provide for an assessment of the effectiveness of any remedial measures taken in the event of seepage.

3. These aspects all serve to provide regulatory and public confidence in CO_2 geological storage activities. Without fulfilling these aims project owners cannot be considered to act as a responsible operator and are unlikely to run a well-managed geological storage operation. Subsurface monitoring is therefore an important input to any necessary host country approval of the project activity, its validation, registration, and verification. These aspects are reflected in the technical guidelines outlined below.

4. Subsurface monitoring activities are specific to a storage site and must be risk-based, and therefore they must be linked to identified features from the *Geological Storage Site Selection & Characterisation Report* and to the risks listed in the *Risk Assessment.* This should inherently link to the main components of the GCC methodology, namely the requirements outlined in *Step 6a* on *Monitoring and management of the geological storage site* through:

(a) Monitoring appropriate modes of operation;

(b) Monitoring of CO_2 migration, and definition of subsurface project boundaries;

(c) Monitoring of geological storage site features;

5. Monitoring should also include direct monitoring of surface and near-surface sensitive domains surrounding within the geological storage complex (geosphere, hydrosphere, biosphere, and atmosphere). The monitoring plan should adequately cover the project boundaries, as described in the relevant PSF.

6. Monitoring in many cases is only useful if results can be calibrated against agreed base-level conditions. Therefore, base-level survey data must be collected prior to commencing CO_2 injection operations, guidance for which is described below.

7. The technical guidance covers three main components for designing an appropriate geological storage site monitoring plan for a GCC project activity, covering:

   I. **Introduction:** the name of the geological storage site and injection formation to which the monitoring plan applies, and a summary of the planned monitoring activities;
   II. **Monitoring plan design and implementation:** identifying the specific techniques that can monitor *modes of operation*, *CO_2 migration,* and *features* in the geological storage site. Techniques for monitoring surrounding domains should also be identified and described in terms of location and frequency;
   III. **Base-level survey:** measurements of background readings prior to injection as required for the calibration of monitoring results from certain techniques;

8. Project participants are required to complete each section of the report and submit it alongside the PSF for the project activity for review by any relevant authorities in the host country (and its appointed bodies), and verification by an accredited entity. Specific monitoring techniques determined following this guidance should be described in detail in the PSF following the relevant monitoring data/parameter tables in the GCC methodology.

9. During implementation, monitoring reports should be prepared in accordance with the guidance provided in Parts C and D of this Section (4): *Monitoring Reports* and *Updating Monitoring Plans*.

10. Note: subsurface monitoring technologies are evolving over time as experience with different techniques at existing CO_2 storage projects takes place. Consequently, the guidance provided here should be regularly updated to reflect the evolution of learning. The approach outlined here includes the major components for geological storage monitoring. Derogations, deviations, and additions from the approach are permissible so long as the rationale for such modifications is described by project owners.

11. The analysis requirements outlined in this guidance should only be implemented by specialist teams that include qualified experts as needed, such as geologists, geophysicists, geomechanics, geochemists hydrogeologists, and petroleum and reservoir engineers.

B. TECHNICAL GUIDANCE FOR COMPILING A GEOLOGICAL STORAGE SITE MONITORING PLAN & REPORT

I. Introduction

1. Name of the selected Geological Storage Site

Please indicate:

(a) The name of the geological storage site and injection formation to which the monitoring plan applies

(b) The version number of this report

(c) The date the report was completed

(d) The name and function of the lead author

(e) The name and the function of the lead peer reviewer

2. Brief description of the monitoring plan

Provide a brief overview (no more than half a page) describing the base-level data collected and the main techniques to be employed for the monitoring.

II. Monitoring plan design and implementation

Monitoring plan design and implementation consists of the process for selecting various monitoring techniques, locations, and frequencies of application.

The monitoring plan should adopt a risk-based approach to its design. The risk assessment compiled (described in Section 2) should be used to identify the range of monitoring needs for risk management purposes.

The monitoring plan shall be developed cognizant of the objectives and requirements described in Section 4, Part A, paragraphs 1 and 2.

3. Technique selection

A wide range of potential techniques should be considered. As a minimum, techniques listed in Annex 5.1 (including Tables A5.1 to A5.6) of Volume 2, Chapter 5, of the 2006 IPCC Guidelines should be considered for their suitability.

Choices of technique, their base level data needs, locations, and frequency of application should be carefully considered, recognizing the data needed to support the implementation of the CDM methodology. Each technique listed in Table A 5.1 of the IPCC Guidelines as well as other relevant techniques should be assessed, and the following documented:

(a) **Rationale:** the rationale for the choice of technique in terms of its capacity to detect CO_2 migration (including lateral and vertical boundaries); changes in the characteristics of identified features; to support appropriate modes of operation; and analysis of surrounding domains. This should include generalised descriptions of the rationale for not including certain techniques listed in Table 5.1 of IPCC, 2006. The rationale can include technical limitations, the status of the development of the monitoring technology, and cost considerations where applicable;

(b) **Locations:** a description of the locations in the geological storage complex where the technique will be applied (for *in situ* passive techniques) or broader descriptions for intermittent mobile techniques. The monitoring location and special sampling rationale should also be provided;

(c) **Project phase and frequency:** a description of how often the technique will be applied and in which phases of the project (operational phase and post-injection phase etc.) or depending on the timeline (e.g.

2, 5, 10, etc. years after injection stops). The temporal sampling rational should also be provided. Some of the monitoring techniques may be only used in case irregularities are observed. Information of contingency monitoring should also be described;

(d) **Base level survey:** an indication of the base-level data needs and sources in order to calibrate monitoring results should be provided. These will provide the basis for the data collected under Section 4;

These data should be compiled following Table 4.1 template below.

Specific details for each monitoring technique data type/unit, location, frequency etc. should be provided in the PSF. Maps and other graphical data which can assist in describing the monitoring technique choice and location should also be provided.

Table 4.1. **Geological Storage Site Monitoring Technique Selection Matrix**

Technique	Rationale				Base level data	Locations (including depth interval when relevant)	Project phase and frequency of application
	CO_2 Migration ($M_{CO2,j/k/l,y}$)	Features ($M_{SC,j/k/l,y}$)	Modes of operation ($P_{M,j/k/l}$)	Surrounding domains			
Technique j	Describe the rationale for the choice of method in terms of detecting CO_2 Plume Migration and vertical and lateral boundary locations, where applicable (if not applicable insert “n/a”). Information should be related to the risk management measures, where applicable, compiled in Table A.2.	Describe the rationale for the choice of method in terms of detecting changes in Features, where applicable (if not applicable insert “n/a”). Information should relate directly to the initial risk register of Features compiled in Table A.2.	Describe the rationale for the choice of method for monitoring appropriate Modes of Operation (if not applicable insert “n/a”). Information should be related to the risk management measures, where applicable, compiled in Table A.2.	Describe the rationale for the choice of method for monitoring surrounding domains (if not applicable insert “n/a”). Information should link to the consequence analysis compiled in Table A.2.	Identify and describe any base-level data needs. Indicate if available from other survey activities or whether new data acquisition is required.	Describe the number of sensors needed (where applicable) and their locations. Details for each monitoring location should be provided in the PSF for the project activity, Section 7.1. The rationale for the location should be provided.	Describe the frequency of application (e.g., passive/continuous; quarterly; once per year; every five years, etc.) depending on the project’s phase. Details should be included in the PSF for the project activity, Section 7.1. The rationale for the frequency should be provided.
Technique k							
Technique l							
... Technique z							

4. Justification of the Proposed Monitoring Plan

The project owner should document:

(a) How the resulting proposed monitoring plan is connected to the risks identified in the risk assessment. Specifically, the monitoring plan should address the risks previously listed, recognizing that one monitoring technique can address several of the risks. The project owner should describe why the technique, or the combination of techniques is appropriate to address a specific risk from both a technical and a cost-efficiency point of view. (The project participant can use the template in Table 4.2 below for this task)

(b) How the resulting proposed monitoring plan will fulfill the objectives as set out in Section 4, Part A, para 1 and 2. This can be documented using the template Table 4.3 below or similar.

Table 4.2. Overview of the monitoring methods addressing the risks identified

Risk	Monitoring technique	Rational
Risk *i* from the risk register *Note that the risk considered acceptable without monitoring in the risk register does not necessarily need to be listed here*	*Technique j from Table 4.1*	Description of the rational
	Technique k	
	Technique l	
	Technique m	
	….Technique z	

***Table 4.3.* Justification that the proposed monitoring plan meets the required objectives**

	The proposed monitoring plan is sufficient to address the objective: *(YES/NO)*	**Monitoring technique**	**Justification**
To assure the environmental integrity and safety of the geological storage site			
To confirm that the injected CO_2 is contained within the geological storage site and within the project boundary			
To ensure that injected CO_2 is behaving as predicted to minimize the risk of any seepage or other adverse impacts			
To ensure that good site management is taking place, taking account of the proposed conditions of use set out in the site development and management plan			
To detect and estimate the flux rate and total mass of CO_2 from any seepage (in particular $S_{k,area,}$ and $S_{FLX,k,y}$)			
To determine the reductions in anthropogenic emissions by sources of GHGs and removals by sinks that have occurred as a result of the registered CCS/DACCS/BECCS project activity			
Provide for measurement of the CO_2 stream and composition, including impurities, at various points in the CO_2 capture, transportation, and storage chain, including at the point(s) of injection into the geological storage site, at an appropriate frequency; (as per the CDM "TOOL08: Tool to calculate emissions from a gaseous stream").			
Provide for measurement of the temperature and pressure at the			

top and bottom of the injection well(s) and observation well(s), at an appropriate frequency;			
Provide for the monitoring and measurement of various geological, geochemical, and geomechanical parameters at an appropriate frequency (e.g., fluid pressures, displaced fluid characteristics, fluxes, and microseismicity)			
Provide for the monitoring and measurement of relevant parameters in the overburden and surrounding domains of the geological storage complex which shall be calibrated to detect early signs of seepage where feasible and at an appropriate frequency (e.g., the monitoring of groundwater properties, soil gas measurements; surface concentrations of CO_2 in the air)			
Provide for the detection of corrosion or degradation of the transport and injection facilities			
Provide for an assessment of the effectiveness of any remedial measures taken in the event of seepage.			

5. Retention and storage of the data

The project owner should document how both raw monitoring data and processed data will be stored (including long-term retention of the data). This should include information on:

(a) Entity(ies) responsible for information retention

(b) Format of the data (paper, electronic, etc...)

(c) Time frame for the storage of data (in particular post-injection)

(d) How the data will be transferred in case of a transfer of liability

III. Base Level Survey

A base level survey involves data collection activities in the *development* phase of a GCC CO_2 capture, transport, and storage activity that can be used to calibrate monitoring data collected during the *operational* phase of the project.

In some situations, base level data may be obtained from existing datasets from site characterization or require additional data collection activities. Data may also be available from broader environmental impact assessment activities, although EIA procedures cannot be relied on to gain suitable data for base level data needs.

Prior to commencing base level survey activities, an evaluation of the data needs should be carried and cross-referenced with existing datasets from site characterization and EIA activities.

Key data needs for base-level survey measurements in relation to the risk management may include *inter alia*:

(a) **Subsurface**: data which can support analysis of CO_2 plume migration and features monitoring. This includes geochemical and geophysical data such as:

- *Brine aquifers*: fluid and gas composition plus pressures and temperatures of the containment systems in the proposed geological storage site in order to detect any changes due to CO_2 contamination from migration/seepage during injection operations and post-injection;
- *Wells*: cement integrity logs, annulus pressure, wellhead pressure, bottomhole temperature and pressure, mineralogy, fluid analysis to support ongoing modes of operation analysis and well-bore integrity assessments during injection operations;
- *Gravity*: gravimetric data to support time-lapse gravity surveys of the geological storage site;
- *Seismic*: to support micro-seismic monitoring of geological storage site features (faults, fissures etc.) for signs of reactivation. Fluid analysis from advanced seismic techniques. Other seismic data may be available from storage site characterisation activities;
- *Topography/relief*: support time-lapse measurements of micro-changes in surface relief due to structural deformation effects of CO_2 injection operations. Satellite data of surface topography may be readily available without the need to collect specific data available. These data can provide proxy measures of CO_2 migration;

(b) **Surface and near-surface:** data which can support early warning signs of seepage, support seepage quantification, and provide a baseline for any remediation measures, such as:

- *Soil gas*: to support repeat measurements of soil CO_2 flux rates, concentrations and geochemical compositions and fingerprints (isotopes). Base data may be needed against which to calibrate quantification measurements in the event that seepage is detected. Base-level measurements may need to characterize natural diurnal, seasonal, and annual variations in natural CO_2 fluxes from soil;[19]

- *Potable aquifers*: pH, elemental composition of the fluid, and dissolved gases plus their isotopic signatures to detect any changes due to CO_2 contamination from migration/seepage post-injection.

(c) **Surrounding domains**:

- *Ecosystems*: surveys may be required to provide base-level data from which changes in certain ecosystems can be identified if seepage occurs. The sensitivity of ecosystems should be established during geological storage site risk assessment under Section 2.

A range of other novel techniques may also require base-level data to be collected (e.g., satellite hyperspectral imaging).

Base-level survey activity should be documented in this section of the report where these are additional to data collected during the *Geological Storage Site Characterisation* (see Section 1). The data compiled should be documented in Table 4.4. below. These data should correspond to the information compiled in Table 4.1.

[19] Caution also needs to be applied when using of soil gas and soil CO_2 flux measurements for leakage detection versus leakage quantification. Field tests have indicated that significant variability can be driven by natural factors. Various issues and options are described in the extant literature (e.g., Romanak, Yang, and Darvari. *Energy Procedia* 114 (2017) 3855-3862; Salmawati et al. *Environmental Monitoring and Assessment* 191 (563) (2019).

Table 4.4. **Base-level survey data collected**

Technique	Base-level data or data number	Date and time	Location	Reading(s) (including) $BD_{SC,j/k/l}$	Notes and rational
Technique k (list all the techniques selected as described in Table D.1)	*Data j* When data from the characterization have been used, they should be referenced here.	Insert dates and times of survey data collection, or start and end dates for surveys that require time series data.	Provide the grid reference for the location (including depth interval when relevant) of the survey, a description of how the survey was carried out, and ambient conditions	Provide a summary of the results of the survey. Where graphical outputs are included, provide these in separate sections after the Table, and provide a clear cross-reference here.	If no base-level data has been acquired, the rationale should be provided
Technique k	*Data k*				
Technique l	*Data l*				
	...Data z				

C. GENERAL GUIDANCE FOR COMPILING GEOLOGICAL STORAGE SITE MONITORING REPORTS

1. Subsurface monitoring reports for a geological CO_2 storage project activity should contain the results of the application of the techniques selected following guidance in Parts A and B of this Section and used to support Sub-step 6a in the relevant GCC methodology. This entails a comparison of the results with predicted behaviour (history-matching), analysis of features for signs of deviations from base-level conditions (which could indicate activation as a seepage pathway), and ensuring appropriate modes of operation are adhered to. The results of this analysis should ensure that evaluations of storage performance and zero-seepage assumptions derived from site selection and characterization are valid (see Section 1).

2. Monitoring results shall also provide indications of significant irregularities, including the detection and quantification of seepage, as described below.

3. Even with the most rigorous data collection and storage site design and analysis, some deviations from predicted CO_2 migration behaviour post-injection may occur. Moreover, the commencement of injection operations and initial monitoring results will result in a rapid increase in understanding of the subsurface geology, storage performance, and reservoir engineering assessments. As such, it is critical to adopt an adaptive learning process based on iterations of the procedure: characterize (including model) → assess the risk → monitor → [repeat], etc. This is achieved through the process of history matching and updating of monitoring plans and model predictions.

4. To achieve its purposes, monitoring activities must be undertaken in all phases of the GCC project activity (i.e., development, operation, post-injection). The techniques, locations, and frequency of monitoring will change over time as both the understanding of the subsurface increases and the risk profile changes, both of which serve to modify the objectives of monitoring. This profile ranges from:

   (a) **Early-operation phase:** intensive monitoring in the early operational phase (e.g., years 1-7 or so) to test the efficacy of certain techniques, test assumptions in performance assessment, recalibrate models and monitoring plan design, and incorporate any new data from injection wells;

   (b) **Mid-operation phase to cessation of injection:** a move towards more routine monitoring (e.g., years 7-20+) when the reliability and effectiveness of certain techniques have been assured, and increasing convergence between observed and predicted behaviour is achieved during history matching;

   (c) **Post-injection phase:** reducing risk as CO_2 migration decreases and stabilization of the CO_2 plume occurs. Evidence of different CO_2 trapping mechanisms was sought during monitoring to support forecasts of long-term distribution of CO_2 and containment security. Eventually, cessation of regular monitoring and a move towards event-based monitoring (i.e., initiation of monitoring linked to any events that could destabilize storage) may occur (see section 14.3).

5. Where significant deviations from monitoring results, including history-matching, occur various requirements apply in respect of updates to monitoring and other aspects apply (see also Appendix B of the Annex to Decision 10/CMP.7, paragraph 13). To address these requirements, technical guidelines are provided below for updating monitoring plans and other aspects associated with appropriate management of a geological storage site (e.g., re-characterization, re-assessment of risk, etc.).

6. A Quality Assurance and Quality Control procedure is outlined at the end of the Section, which is designed to ensure that effective decision-making has been employed during the compilation and analysis of monitoring results and updates to the monitoring plan. The procedures outlined there must be followed at each stage when preparing a Monitoring Report.

7. The analysis requirements outlined in this guidance should only be implemented by specialist teams that include qualified experts as needed, such as geologists, geophysicists, geomechanics, geochemists hydrogeologist, and petroleum and reservoir engineers. Verification of monitoring reports for the subsurface component of a CO_2 capture and geological storage can only be conducted by verifiers accredited to a Sectoral Scope 16, Carbon Dioxide Capture and Geological Storage.

D. TECHNICAL GUIDELINES FOR COMPILING GEOLOGICAL STORAGE SITE MONITORING REPORTS

I. Monitoring results

D.1 Description of the Data Acquired and the Processing

The project owner should first document the monitoring performed. This section aims to demonstrate that the monitoring plan (as defined in the PSF) has been followed and to list the data that will be used for the performance assessment. Any deviation from the original monitoring plan should be described and fully justified. The data acquired should be listed and documented using the following (or similar) template:

Technique	*Technique i*
Data/Parameter	
Unit	
Description	
Source of data (i.e., location of the measurement, incl. depth interval if relevant)	
Measurement methods and procedures	
Monitoring frequency	
QA/QC procedures	
Processing (e.g., for seismic data) and interpretation performed (if relevant)	
Rationale for the deviation from the monitoring plan.	

D.2 Performance Assessment and History Matching

The observed results shall then be compared with the behaviour predicted in dynamic simulation of the 3D models of CO_2 and other fluid movements, pressure, volume, and saturation behaviour and geochemical models undertaken in the context of the storage security and site characterization and used to interpret whether site performance is consistent with predictions and modelling; where there is a significant deviation between the observed and the predicted behaviour, the static and dynamic models shall be recalibrated to reflect the observed behaviour.

Model recalibration shall be based on the data and observations from the monitoring plan, and where necessary to provide confidence in the recalibration assumptions, additional data shall be obtained; ***Equation 21*** to provide the methodological basis for comparing monitoring results with predicted performance.

The monitoring report should outline monitoring data that can support these requirements, based on the techniques selected following guidance in Parts A and B of this Section (4).

The project owner should describe the history matching performed and should document (if relevant) each of the models used:

(a) Version of the model, and a brief description of the different past versions of the model (incl. key changes)

(b) Scale/scope of the model

(c) Methodology and results of the history matching

(d) Summary of the key changes performed on the model

(e) Key assumptions (including boundaries conditions applied)

(f) The sensitivity/uncertainty analysis method(s) used

The project participant shall then provide information on the following:

(a) **Conditions of use** *(Equations 19 and 20* in the GCC methodology): demonstrating that the injection formation has been operated within safe modes during the monitoring period; and,

(b) **CO_2 migration analysis** *(Equations 21 and 22* in the GCC methodology): images of the geological storage site which provide information regarding the behaviour of the injected CO_2 plume to support reviews of the subsurface project boundaries post-commencement of injection operations; and,

(c) **Geological storage site architecture** *(Equations 23 and 24* in the GCC methodology): signs of significant irregularities within features of the geological storage complex as defined during geological storage site characterization, including recognized migration and seepage pathways, and any other previously undetected features.

Results should indicate whether the geological storage site is performing satisfactorily, or whether significant irregularities have occurred.

D.3 Significant Irregularities and Corrective Measures

Equations 19, 21, and 23 in the GCC methodology provide the basis for determining whether significant deviations have occurred over the monitoring period. Where results of history matching indicate significant disagreement between predicted and observed results, a description and interpretation of the deviation should be provided in terms of:

(a) **Modes of operation**: reasons why pressure in the injection formation was exceeded and measures to correct the irregularity.

(b) **Lateral or vertical migration**: reasons why CO_2 migration beyond the subsurface boundaries could have occurred in a way that wasn't predicted in the performance assessment, and measures to correct the irregularity.

(c) **Activation of features**: reasons why a feature could have been activated, and measures taken to correct the irregularity.

Information generated for all elements should be used to update the risk assessment and the monitoring plan (Section II below).

Where any corrective measures have been undertaken to remediate seepage or potential seepage resulting from the activation of emission pathways, these should also be documented in the Monitoring Report. This should include a description of the measures undertaken, the outcome, and the means of assessing the success of the measures undertaken. Key remaining uncertainties should be described.

D.4 Estimated Seepage

Indicate whether a significant irregularity included seepage (yes/no).

If yes, information regarding the following should be included in the monitoring report

(a) **Emissions pathway**: details of the emissions pathway(s) by which seepage occurred, including details of how this was established;

(b) **Flux rate**: estimated flux rate of the emissions pathway at the surface or into the hydrosphere (in $tCO_2/m^2/day$), and how the estimate was established;

(c) **Duration**: estimated duration of the seepage (in days), and how this was established;

(d) **Area**: the areal extent of the identified seepage zone (in m^2) associated with the emission pathway, and how this was established;

(e) **Uncertainty**: an overall estimate of the uncertainty of the result, including a description of the factors used to determine the accuracy and uncertainty of measurements undertaken.

The mass of CO_2 estimated to have seeped should be calculated following *Equation 25* of the methodology and corrected by a conservative estimate of uncertainty for each parameter to determine the final reported mass of seeped CO_2 (using *Equation 27* where necessary). A conservative estimate can involve expert judgment.

II. Updates to Monitoring Plans

To account for improvement in understanding of the subsurface as a result of subsurface monitoring activities, and to accommodate the changing objectives of subsurface monitoring over time, the following analysis should be carried out through the project life-cycle:

(a) Review of the characterization of the geological storage site (per Section 1);

(b) Update of the risk assessment (per Section 2), if necessary;

(c) Review and update, if necessary, the Site Development and Management Plans (per Section 5);

(d) Updating or re-design of the monitoring plan (where necessary – this Section 4, Part D).

These procedures must be carried out if a significant irregularity has occurred.

D.05 Review of the Characterization of the Geological Storage Site Data

History-matching of observed and predicted CO_2 migration behaviour allows for a reinterpretation of the containment system characteristics and engineering considerations (e.g., trap structure/geometry and dip; hydrogeology/flow; compartmentalization; heterogeneity; permeability; features, etc.).

The new knowledge gained should be used to update data collected under the *Geological Storage Site Selection & Characterisation Report*, and subsequently to re-appraise storage performance in terms of capacity estimates, CO_2 migration analysis, and features analysis compiled in the *Geological Storage Site Selection & Characterisation Report*.

The review should be performed following the guidance in Section 1.

D.06 Re-assessment of risks

Any new risk features identified during monitoring activities should be documented and included as an update to any risk assessment and any risk register.

The update process for the risk assessment is documented in Section 2.

D.07 Review and update Site Development and Management Plans

When relevant new findings from the *Risk and Safety Assessment* should be incorporated and included as an Addendum to the *Site Development and Management Plans*.

D.08 Update Monitoring Plan

New findings from subsurface monitoring and an update of the site characterization must be used to re-assess the efficacy of the geological storage site monitoring plan.

(a) **Knowledge gaps**: identifying and applying new or additional techniques/locations/frequencies that could fill gaps apparent in information and understanding of the subsurface;

(b) **New Features**: identifying and applying new or additional techniques/locations/frequencies for certain monitoring techniques in relation to any new Features identified in the geological storage site;

(c) **Efficacy**: removing some techniques from the monitoring plan where they have proved ineffective or unnecessary;

Where necessary, an addendum to the *Geological Storage Site Monitoring Plan* should be prepared and submitted in conjunction with Monitoring Reports.

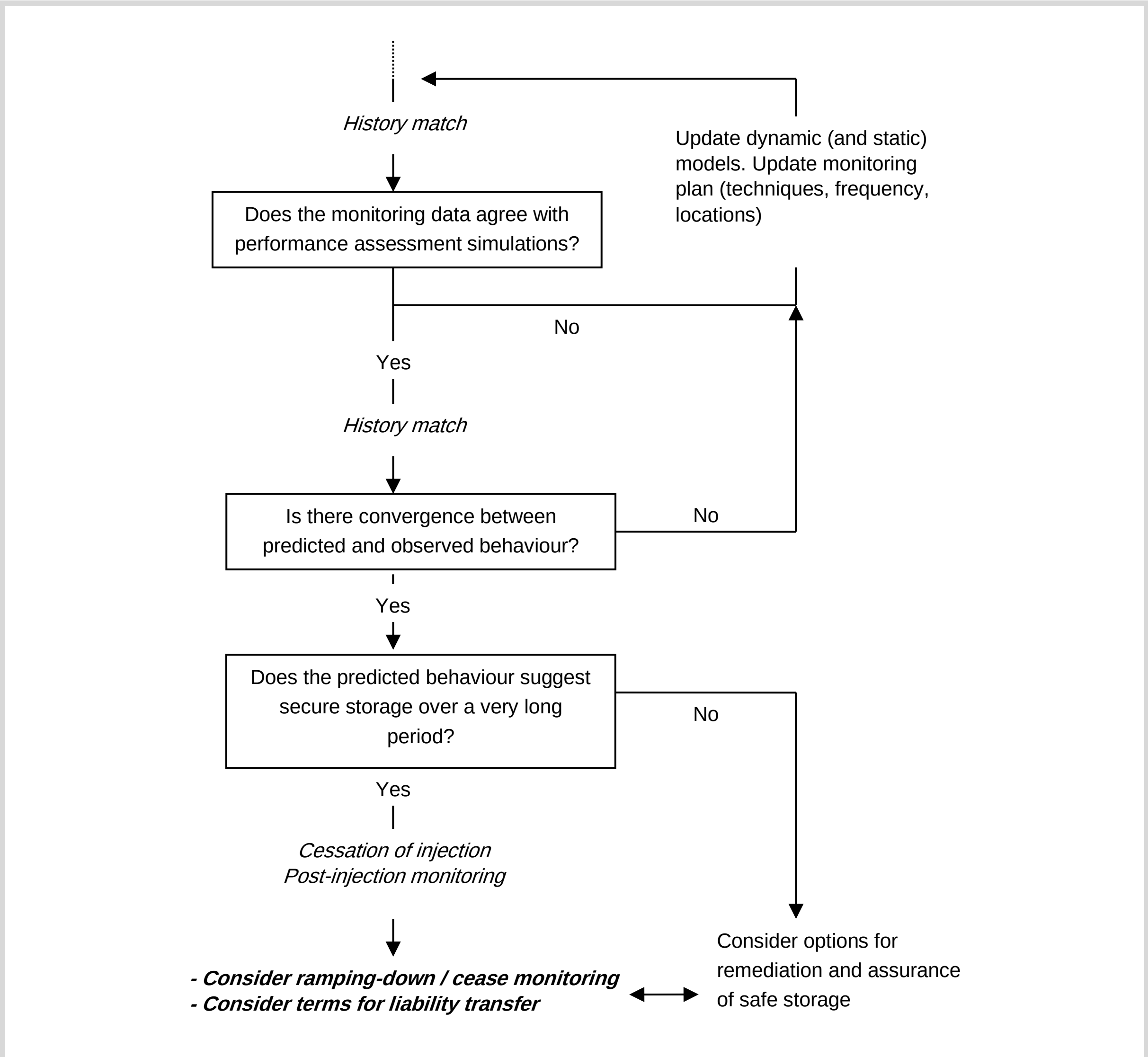
The addendum should include a revision of the justification of the Monitoring plan including a revision of information contained in Tables D.2. and D.3.

III. Quality Assurance and Quality Control

The QA/QC outlined in Figure D.1 should be tested against the results of the monitoring plan.

For updates to the monitoring plan, the QA/QC considerations outlined in Figure D.1 should be applied. These procedures may be applied several times across the projects life-cycle to support liability considerations, including liability transfer.

Figure D.1 **Additional QA/QC for Updates to Monitoring Plans**



5. Site Development and Management Plans

A. GENERAL GUIDANCE FOR GEOLOGICAL STORAGE SITE DEVELOPMENT AND MANAGEMENT PLANNING

1. Drawing on steps 1 to 3 described in Section 1, project owners should present a geological CO_2 storage site development and management plan. The plan should include:

Project Management Plans

2. The *general* project Management plan should include:

   (a) The description of the different activities, the schedule, and the resource plan (including subcontractors role)

   (b) The key responsibilities

   (c) The key decision gates and decision mechanisms

Plan for the preparation of the site (Surface)

3. The plan for the preparation of the geological storage complex should include[20]:

   (a) Outline engineering requirements for the modifications of the existing infrastructure (e.g., foundation, pavement, and road, surface facilities, subsea equipment, electricity/power supply, etc.) and

   (b) Outline engineering requirements for new facilities (e.g., pipelines, tanker loading/unloading, temporary storage, electricity/power supply, CO_2 injection equipment, data center, personnel facilities, etc.).

4. If a range of different options are under consideration a summary should be provided for each option

Plan for well construction and remediation

5. The plan for well construction and remediation should include[21]:

[20] Adapted from (2)
[21] Adapted from (2)

(a) Plans for re-entry/remediation operations for existing wells (if relevant) including outline engineering requirements, materials and techniques used, etc.

(b) Injection, monitoring, and water production well locations, well construction and design, and construction procedures; including:

(i) Well location and trajectory

(ii) Well drilling, cementing, logging, and completion plans

(iii) Well materials and consumables

(iv) Techniques used

(c) Further data acquisition is planned as part of the well construction.

Injection, operation, and maintenance plan

6. The injection, operation, and maintenance plan includes high-level operational constraints for the operation of the site. The operational constraints of use should ensure that geophysical, geo-mechanical, and geochemical processes in the injection formation are within accepted levels of safety i.e., within levels that avoid the risk of seepage processes within the geological storage site (based on the site characterization and the risk assessment)

7. The plan should include (where relevant):

(a) Operational constraints

(i) The ranges of volumes, rates, and composition of the CO_2 streams to be injected over time including acceptable ranges and maximum allowable limits;

(ii) The maximum allowable injection and/or near-wellbore pressure[22]; the extent of the pressure front within the geological storage site and surrounding domains, and the strategy for managing reservoir pressure ($P_{PC, SL}$);

(iii) The injection procedures.

(b) Initial plan to update the model(s), and simulation(s), including calibration and update of static and predictive models through history matching of monitoring data; this section should include the description of the methodology proposed to update the assessment of the vertical and lateral boundaries of the dispersing CO_2 plume over time.

[22] Depending on near well bore temperature.

(c) Initial plan to update uncertainty and risk assessment (following the guidance in Section 2)

(d) Tentative schedule for updating performance targets with up-to-date injection history and results of modelling and monitoring.

(e) Operating and maintenance programs and protocols, including staff training plans.

8. The injection, operation, and maintenance plan should justify how the operational constraints described support the zero-seepage assumptions by avoiding conditions that could lead to seepages.

Preliminary Plan for Cessation of Injection and Site Closure

9. The preliminary plan for cessation of injection and site closure should include (where relevant):

(a) Conditions required for the closure of the site and contingency plans if the conditions are not met;

(b) Initial plan for meeting any liability arrangements required by a host country authority and the length of time these may be in force;[23]

(c) Planned injection/production/monitoring well abandonment and plugging procedures (e.g., details of methods employed for decommissioning, equipment removal, cased hole logging, testing, plugging, and abandoning);

(d) Planned surface infrastructure and equipment shutdown and decommissioning procedures;

(e) Planned monitoring and verification operations, including planned surveying, data acquisition/recording, and processing stages during the post-injection phase;

(f) Planned updates of the models (static and dynamic); performance assessment, risk assessment, and risk management plan.

[23] This section will depend on the host country specific requirements, per paragraph 193~197 of the Methodology for project activities involving the capture, transport and geological storage of carbon dioxide Version 1.1

DOCUMENT HISTORY

Version	Date	Comment
V1.1	01/04/2024	Final version for publication
V1.0	13/03/2024	Draft version for Regulatory Committee approval

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